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DESCRIPTION**METHOD AND SYSTEM FOR WAFER AND DEVICE-LEVEL TESTING OF AN INTEGRATED CIRCUIT****BACKGROUND OF THE INVENTION****1. Technical Field:**

The present invention relates in general to testing electronic devices and, in particular, to testing integrated circuits. Still more particularly, the present invention relates to a method and system for wafer and device-level testing of integrated circuits such as logic devices.

2. Description of the Related Art:

Integrated electronic circuits, such as logic devices, are often designed to use external devices, such as dynamic random access memories (DRAMs), to provide data storage in electronic systems, such as computer systems. To ensure proper operation of the electronic systems, the manufacturing process for integrated circuit logic devices includes a number of testing steps intended to verify that the logic devices will provide reliable performance over the expected lifetime of the electronic systems in which they are installed.

A typical manufacturing process for logic devices begins with the fabrication of a semiconductor wafer containing hundreds or even thousands of identical dice. The circuitry in each logic device using external DRAM generally includes integrated DRAM interface circuits for storing data into and retrieving data from the DRAM's memory array and performing other operations in response to memory requests or commands.

Following wafer fabrication, a quick wafer probe is performed in an attempt to

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identify dies on the wafer having defects. The wafer probe often tests only a small portion of the circuits in the DRAM interface utilizing clock rates that are lower than normal operating frequencies.

5 Following the wafer probe, the wafer is scribed into dice. Dice marked as faulty after the wafer probes are discarded, and dice passing the wafer probe are packaged to obtain logic devices. Packaging technologies that are commonly used for logic devices include, among others, ball grid array (BGA) and wire bond.

10 After packaging, the logic devices are subjected to device-level testing. Device-level testing, like the wafer probe tests, may include low frequency tests of the DRAM interface circuits. Device-level testing may also include a "burn-in" test in which the packaged logic devices under test are subjected to high ambient temperatures and tests of long duration in order to discover early life failures. Device-level testing also differs
15 from wafer probe testing in that, in addition to basic pattern testing of the DRAM interface circuits, device-level testing generally tests the DC and AC characteristics of the logic and operation of the memory interface. Device-level testing also differs from wafer probe testing in that device-level testing is typically performed at or near the rated signal frequencies of the external DRAM, and these frequencies often require more
20 sophisticated and expensive test equipment.

 Logic devices with DRAM interface circuitry that pass the device-level test may subsequently be assembled onto circuit cards to form logic boards such as computer main boards and Peripheral Component Interconnect (PCI) expansion boards. Each
25 logic board is then typically subjected to a final, intensive fault test prior to shipping or installation. The faults detected by board testing include faults in the circuit cards themselves (e.g., open or shorted traces), faults introduced by board assembly (e.g., damaged pin drivers, open or shorted pins, and ESD damage), and undetected faults in the logic device circuitry. Following completion of testing, logic devices and boards
30 that pass can then be installed in an end-use application.

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One drawback of the conventional logic device manufacturing process outlined above is that a number of faults are not discovered until late in the manufacturing process, for example, during device-level and board testing. As appreciated by the present invention, if such defects could be detected earlier in the manufacturing process (i.e., during wafer testing), the significant expense associated with packaging and board assembly of the defective dice could be eliminated. Unfortunately, the expense of the sophisticated test equipment currently required to fully exercise integrated DRAM interface circuitry prohibits its use during wafer testing.

A second drawback of the conventional manufacturing process is that several different pieces of specialized test equipment are required to fully test many integrated circuit logic devices. For example, to test the DRAM interface of a logic device, an algorithmic tester is utilized to stress the AC timing of a predetermined parameter for memory accesses. A separate vector tester is utilized to exercise the built-in self-test (BIST) functions of the logic device. A third system tester is often employed to verify proper operation of external DRAM in response to commands. As will be appreciated, the use of multiple testers compounds the expense of testing.

A third drawback of the prior art is that conventional test equipment does not fully emulate the intended end-use environment of devices under test. In particular, conventional testers for packaged logic devices and boards have a fixed input impedance. This input impedance cannot be adjusted and may result in test behavior that is quite different from the operating behavior of the logic with DRAM interface device under test when it is eventually installed in an end-use environment. Consequently, there may be an unacceptably high number of faulty devices or boards that pass the test process and even some satisfactory devices that fail the test process.

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SUMMARY OF THE INVENTION

The present invention overcomes the foregoing and additional shortcomings in the prior art by introducing an improved method and system for wafer and device-level testing of integrated circuits such as logic devices with DRAM interface circuits.

According to a preferred embodiment of the present invention, a tester comprises test logic and a connector for at least one device under test. The connector, which may comprise a wafer probe for dice on a wafer or a test fixture for packaged integrated circuit devices, has connections for the device under test that present an impedance selected to emulate the characteristic impedance of an end-use environment of the device under test. For example, in an embodiment in which the device under test comprises logic devices using Rambus™ Signal Levels to interface to memory and the end-use environment is a Rambus™ channel connecting to Rambus DRAMs (RDRAMs), the characteristic impedance is between approximately 20 and 60 ohms. If, on the other hand, the end-use environment is connection to a socket for Rambus™ memory modules, then the characteristic impedance is approximately 28 ohms. Alternatively, if the end-use environment is connection to a socket for double data rate (DDR) memory modules, then the characteristic impedance is approximately 60 ohms. Thus, the tester of the present invention can accurately simulate operational behavior in an end-use environment of the device under test. Because this accurate simulation is available even for dice on a wafer, the needless expense associated with packaging defective dice and assembling defective dice onto boards can be avoided.

The test logic, which is coupled to the connector for communication with the device under test, transfers test commands and test data to the device under test. The test data and commands are utilized to perform multiples types of tests, including tests of the core logic and interface logic of the device under test. In this manner, the need for multiple types of testers is reduced or eliminated.

Additional objects, features, and advantages of the present invention will become apparent from the following detailed written description.

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BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself however, as well as a preferred mode of use, further objects and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Figure 1 is a high-level block diagram of a logic tester in accordance with a preferred embodiment of the present invention;

Figure 2 is a more detailed block diagram of a first tester logic card in the logic tester illustrated in **Figure 1**, wherein the first test logic card includes tester logic for testing a device under test (DUT) having a Rambus™ memory controller;

Figure 3 depicts a portion of a wafer probe or test fixture for packaged devices having selectable termination impedance and propagation delay in accordance with a preferred embodiment of the present invention;

Figure 4 is a high level flowchart of an exemplary test process in accordance with the present invention for testing logic devices with integrated memory controller;

Figure 5A is a timing diagram illustrating the timing of the clock from master (CFM) and clock from master negative (CFMN) signals provided by the Rambus™ memory controller in the logic device under test in relation to the setup and hold times of WRITE operations;

Figure 5B is a timing diagram depicting the use of a programmable delay in the clock-from-master (CFM) and clock-from-master negative (CFMN) signals provided by the Rambus™ memory controller in the logic device under test to test the timing sensitivity of WRITE operations;

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Figure 6A is a timing diagram illustrating the timing of the clock-to-master (CTM) and clock-to-master negative (CTMN) signals provided to the Rambus™ memory controller in the logic device under test in relation to valid times for READ transactions;

Figure 6B is a timing diagram depicting the use of a programmable delay in the clock-to-master (CTM) and clock-to-master negative (CTMN) signals provided to the Rambus™ memory controller in the logic device under test to test the timing sensitivity of READ operations;

Figure 7 illustrates a first alternative embodiment of a logic tester in accordance with the present invention for testing DUTs having Rambus™ memory controllers;

Figure 8 illustrates a second alternative embodiment of a logic tester in accordance with the present invention for testing DUTs having Rambus™ memory controllers;

Figure 9 illustrates a third alternative embodiment of a logic tester in accordance with the present invention for testing DUTs having Rambus™ memory controllers;

Figure 10 illustrates a fourth alternative embodiment of a logic tester in accordance with the present invention for testing DUTs having Rambus™ memory controllers;

Figures 11A-11C together illustrate a first fixture embodiment for a logic tester for DUTs already manufactured onto circuit boards in accordance with the present invention, wherein the DUTs contain Rambus™ memory controllers;

Figures 12A-12B together depict a second fixture embodiment for a logic tester for DUTs already manufactured onto circuit boards in accordance with the present invention, wherein the DUTs contain Rambus™ memory controllers;

Figure 13 is a more detailed block diagram of a second tester logic card in the logic tester illustrated in **Figure 1**;

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Figure 14A is a timing diagram illustrating the timing of data and strobe DQS signals provided by a DDR memory controller in a logic DUT in relation to the setup and hold times of WRITE operations;

Figure 14B is a timing diagram depicting the use of a programmable delay in the timing of data and strobe DQS signals provided by the DDR memory controller in a logic DUT to test the timing sensitivity of WRITE operations;

Figure 15A is a timing diagram illustrating the timing of data and strobe DQS signals provided by the DDR memory controller in a logic DUT in relation to valid times for READ transactions;

Figure 15B is a timing diagram depicting the use of a programmable delay in the timing of data and strobe DQS signals provided by the DDR memory controller in a logic DUT to test the timing sensitivity of READ operations;

Figure 16 depicts a portion of a wafer probe or test fixture for packaged devices utilizing DDR memory, where the wafer probe or test fixture has selectable impedance and propagation delay in accordance with a preferred embodiment of the present invention;

Figure 17 illustrates a first alternative embodiment of a logic tester in accordance with the present invention for testing devices having DDR memory controllers;

Figure 18 illustrates a second alternative embodiment of a logic tester in accordance with the present invention for testing devices having DDR memory controllers;

Figures 19A-19C illustrate a first fixture embodiment for a logic tester for testing DUTs having DDR memory controllers, wherein the DUTs are manufactured onto circuit boards;

Figures 20A-20B illustrate a second fixture embodiment for a logic tester for testing DUTs having DDR memory controllers, wherein the DUTs are manufactured onto circuit boards;

Figure 21A is a timing diagram illustrating the timing of the clock-from-master (CFM) and clock-from-master negative (CFMN) signals for logic devices performing WRITE operations using a derivative of Rambus Signaling Levels with more than 2 transfers per clock, such as QSL;

Figure 21B is a timing diagram depicting the use of a programmable delay in the timing of the clock-from-master (CFM) and clock-from-master negative (CFMN) signals for logic devices performing WRITE operations using a derivative of Rambus Signaling Levels with more than 2 transfers per clock, such as QSL;

Figure 22A is a timing diagram illustrating the timing of the clock-to-master (CTM) and clock-to-master negative (CTMN) for logic devices performing READ operations using a derivative of Rambus Signaling Levels with more than 2 transfers per clock, such as QSL;

Figure 22B is a timing diagram depicting the use of a programmable delay in the timing of the clock-to-master (CTM) and clock-to-master negative (CTMN) signals for logic devices performing READ operations using a derivative of Rambus Signaling Levels with more than 2 transfers per clock, such as QSL;

Figure 23A is a timing diagram illustrating the timing of the clock and strobe (DQ) from logic devices performing WRITE operations using a derivative of DDR memory bus technology with more than 2 transfers per clock, such as QDR;

Figure 23B is a timing diagram depicting the use of a programmable delay in the timing of the strobe (DQ) from logic devices performing WRITE operations using a derivative of DDR memory bus technology with more than 2 transfers per clock, such as QDR;

Figure 24A is a timing diagram illustrating the timing of the clock and strobe (DQ) to logic devices performing READ operations using a derivative of DDR memory bus technology with more than 2 transfers per clock, such as QDR;

Figure 24B is a timing diagram depicting the use of a programmable delay in the timing of the strobe (DQ) to logic devices performing READ operations using a derivative of DDR memory bus technology with more than 2 transfers per clock, such as QDR;

Figure 25 is a voltage chart illustrating the effect varying V_{REF} has on the apparent voltage levels of inputs to a DUT when using transfers of Rambus Signaling Levels (RSL) or its derivatives, such as QSL; and

Figure 26 is a voltage chart illustrating the effect varying V_{REF} has on the apparent voltage levels of synchronous dynamic memory bus inputs to a DUT when transfers employ double data rate (DDR) or a DDR derivative, such as QDR.

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DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

With reference now to the figures and in particular with reference to **Figure 1**, there is depicted a high-level block diagram of an illustrative embodiment of a logic tester in accordance with the present invention. As illustrated, logic tester **10** includes one or more (e.g., 64) tester logic boards **12** that each includes circuitry for testing one device under test **14**. In the context of the present invention, a "device under test" (DUT) is defined as either a die on a semiconductor wafer or a packaged integrated circuit device. Each tester logic board **12** is coupled to a host **16** and a power source **18** (e.g., 110 V AC) via a communication bus **20** and a power bus **22**, respectively. Host **16**, which may be a suitably programmed personal computer or a control processor, downloads test procedures and test parameters to and receives test results from tester logic boards **12** via communication bus **20**.

As further illustrated in **Figure 1**, each tester logic board **12** is coupled to a respective DUT **14** by a controlled impedance connector **24** having connection elements suitable for the type of DUT **14** being tested. Thus, if DUTs **14** are logic dice on a wafer, connector **24** comprises a wafer probe; if, however, DUTs **14** are packaged logic devices, connector **24** comprises a test fixture having sites for connecting to packaged logic devices. For flexibility, tester logic boards **12** preferably employ a "universal" interface that can support both types of connectors **24**. Importantly, and as discussed further below, the connection elements of connector **24** present to each DUT **14** a characteristic impedance that is selected to simulate an end-use environment of DUTs **14**.

Referring now to **Figure 2**, there is illustrated a more detailed block diagram of a first tester logic board **12** from **Figure 1** in accordance with a preferred embodiment of the present invention. The depicted embodiment includes circuitry specifically designed for testing logic DUTs having integrated Rambus™ dynamic random access memory (RDRAM) memory control circuitry; however, those skilled in the art will appreciate that the present invention is not limited to testing logic DUTs with RDRAM memory controllers, but is instead applicable to testing other types of integrated circuitry.

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References useful for an understanding of the depicted embodiment of the present invention include the following Rambus™ documentation (which is incorporated herein by reference):

- a) *Direct Rambus™ System and Board Design Considerations*, Rambus, Inc., May 1998;
- b) *RIMM Module Specification*, ver. 1.00, Rambus, Inc.;
- c) *128/144-Mbit Direct RDRAM Data Sheet*, Rev. 1.11, Rambus, Inc., June 2000;
- d) *RIMM Module Design Guide*, ver. 0.90, Rambus, Inc.;
- e) *Rambus RIMM Module (with 128/144-Mbit RDRAMs)*, Rev. 1.2, Rambus, Inc., October 2000;
- f) *Direct Rambus™ RAC*, rev. 1.11, Rambus, Inc., July 24, 2000; and
- g) *Direct Rambus™ Clock Generator Data Sheet*, Rev. 1.1, Rambus, Inc., June 2000.

As shown, each tester logic board **12** includes a state machine or central processing unit (CPU) **30** that controls the testing performed by that tester logic board **12**. CPU **30** receives test procedures, test parameters, test data and expected test results from host **16** via communication bus **20** and communication interface **32**. Based upon these inputs, CPU **30** generates a number of output signals **34-44** (described further below) to orchestrate the operation of the other components of tester logic board **12** during testing.

In addition to CPU **30**, tester logic board **12** includes at least three principal subsystems: cooling subsystem **48**, tester logic **50** and power subsystem **52**. Cooling subsystem **48**, which may comprise, for example, a convection or thermoelectric cooling system, dissipates heat produced by the components of tester logic board **12**. The operation of cooling subsystem **48** is actively controlled by cooling control signals generated by thermal control logic **56** within tester logic **50** in response to the output of a thermal sensor **58**.

Power subsystem **52** includes a power supply **70** that utilizes power received from power bus **22** to provide power with the appropriate voltage and current characteristics to CPU **30** and tester logic **50**. Power subsystem **52** further includes a number of variable voltage supplies **72-78** that provide voltages utilized to operate DUT **14**. In the illustrated embodiment, in which tester logic board **12** is designed to test logic DUTs having Rambus™

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memory controller circuits, variable power supplies 72-78 include variable reference voltage (V_{REF}) supply 72, variable termination voltage (V_{TERM}) supply 74, variable V_{DD} supply 76 and variable V_{DDA} supply 78. Each of variable voltage sources 72-78 outputs a respective selected voltage specified by voltage select signals 44 provided by CPU 30.

Power subsystem 52 finally includes a number of power measurement unit (PMUs) 80, which are selectively coupled to the output pins of DUT 14 by relays 92. Relays 92 can be configured by CPU 30 to route signals present at the output pins of DUT 14 either to tester logic 50 for evaluation of the correctness of their logic states and/or timing or to PMUs 80 for measurement of their DC power characteristics. As described further below, at least one of PMUs 80 measures the source voltage(s) and current supplied to DUT 14 by determining the voltage drop across a test resistor 90. Other PMUs 80 preferably measure the leakage current of the pins of DUT 14.

In addition to the thermal sensor 58 and thermal control logic 56 discussed above, tester logic 50 includes a sequencer 100, which may comprise, for example, a general-purpose processor, a plurality of bit-slice (e.g., 4-bit) processors working in concert, a state machine, or an application-specific integrated circuit (ASIC). Sequencer 100 is coupled to CPU 30 by a communication interface 102 through which sequencer 100 receives test parameters, test data, correct test results, and test procedures, which are stored by sequencer 100 in random access memory (RAM) 104. Sequencer 100 also receives a reset signal 36 that, when asserted by CPU 30, causes sequencer 100 to reset itself to a known stable state by reference to configuration parameters stored within non-volatile random access memory (NVRAM) 106. The operation of sequencer 100 is timed by a clock 108, which may be asynchronous relative to the clocks utilized to operate DUT 14.

Sequencer 100 is further connected to memory 110, which interfaces to DUT 14 through a Rambus™ ASIC cell (RAC) 112 that is coupled to DUT 14 by relays 92 and connector 24. The depicted arrangement of memory 110, RAC 112, connector 24 and DUT 14 simulates the memory subsystem of a personal computer system or other end-use environment of DUT 14. That is, DUT 14, much like the CPU of a computer system, issues

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commands and requests through its integrated memory controller. DUT 14 outputs commands and requests to RAC 112 utilizing high-speed Rambus™ Signal Levels (RSL) or Quad RSL (QRSL) signaling. RAC 112 converts commands, requests, and responses between the RSL or QRSL signaling employed by DUT 14 and the lower-speed CMOS-level signals utilized by memory 110. In addition, RAC 112 functions as a high performance parallel-to-serial and serial-to-parallel converter by packing and unpacking data packets communicated with memory 110 to and from narrower Rambus™ data words. A Rambus Signaling Levels (RSL) bus master 114 is also connected to the RSL pins of RAC 112. The RSL bus master 114 operates using clock 118 and under the control of the sequencer 100 by means of control lines 116.

During testing, sequencer 100 sets parametric controls for testing DUT 14, stores vector information into memory 110 for transfer to the pins of DUT 14, writes instructions and data into memory 110 for retrieval by DUT 14, and receives the results of testing based upon the information measured by the PMUs 80 or stored in memory 110 by DUT 14. In response to receipt of test results for DUT 14, sequencer 100 logs the test results in RAM 104 and compares the test results with correct results also stored in RAM 104 to make a pass/fail determination for DUT 14. Sequencer 100 manages the transfer of vectors by using control lines 116 to instruct RSL bus master 114 to transfer vectors stored in memory 110 to the pins of DUT 14, which is in test mode. DUT 14 interprets the vectors and places a response value onto the pins. Sequencer 100 also manages the transfer of self-test results by using control lines 116 to instruct RSL bus master 114 to store the output values on the pins of DUT 14 in memory 110.

As further shown in Figure 2, communication between RAC 112 and DUT 14 is synchronized by a number of sets of clock signals including clocks 120, which are received by RAC 112 and DUT 14. Clocks 120 are selected by selector 124 from among a plurality of clock signals generated by clock sources 122 in response to clock select signals 38 output by CPU 30. The sets of clock signals utilized to synchronize communication with DUT 14 also include clock-from-master (CFM) clocks 130 generated by DUT 14 and clock-to-master (CTM) clocks 132 generated by RAC 112. In order to test the timing sensitivity of DUT 14,

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CFM clocks 130 and CTM clocks 132 each are passed through a respective one of programmable delays 134 and 136, which applies a delay specified by a respective one of tester logic (TL) delay signal 40 and DUT delay signal 42. Delays 134 and 136 each may be implemented, for example, with a Semtech Edge629 delay circuit and associated Semtech Edge693 driver circuit.

With reference now to **Figure 3**, a detailed depiction of a preferred embodiment of connector 24 from **Figures 1** and **2** is given. The illustrated embodiment, which is suitable for use with DUTs having Rambus™ memory controllers, includes a plurality of sites 150 (only one of which is shown), each of which has connections corresponding to the pinout of a DUT 14. For example, the illustrated DUT 14 is a logic device packaged in a micro-BGA package having a layout of 54 pads 152 in the form of solder balls or spring contacts, such as Microspring™ interconnection elements produced by FormFactor, Inc., of Livermore, California. Accordingly, site 150 has 54 connections 154, each corresponding to a respective one of pads 152. In a preferred embodiment, each connection 154 comprises a spring contact, such as a Microspring™ interconnection element produced by FormFactor, Inc., of Livermore, California.

Although the interconnection of only one connection 154 of site 150 is shown in **Figure 3** for clarity, each connection 154 of a site 150 forms one point of a three-point circuit having RAC 112 and variable V_{TERM} supply 74 as termination points. As noted above, variable V_{TERM} supply 74 can produce a plurality of different termination voltages (represented by voltages V_A - V_Z), only one of which is selected by a selector 160 to be the termination voltage V_{TERM} in response to voltage select signals 44 provided by CPU 30.

Between each connection 154 and each of variable V_{TERM} supply 74 and RAC 112, an impedance and an optional propagation delay element are connected in the signal path. That is, a termination impedance 162 and an optional first propagation delay element 164 are coupled between connection 154 and variable V_{TERM} supply 74, and a test impedance 166 and an optional second propagation delay element 168 are coupled between connection 154 and RAC 112. In accordance with an important aspect of the present invention, the input

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impedance presented by each connection **154** of site **150**, which is the sum of the contact impedance of connection **154** plus the parallel combination of termination impedance **162** and test impedance **166**, is equivalent to the characteristic impedance of an end-use environment of DUT **14**. For example, if the end-use environment is connection to sockets for Direct Rambus™ modules, such as Rambus™ In-line Memory Module (RIMM), Small Outline RIMM (SO-RIMM) or Media RIMM, the characteristic impedance is selected to be approximately $28\ \Omega$, and more particularly, $28\ \Omega \pm 10\%$. If, on the other hand, the end-use environment is a Direct Rambus™ channel, the characteristic impedance is selected to be approximately between 20 and $60\ \Omega$. As shown, in a preferred embodiment, multiple end-use environments can be emulated and non-standard impedances outside of specified tolerances can be supported by implementing termination impedance **162** and test impedance **166** as variable impedances. In this preferred embodiment, a respective selector **160** selects impedances **162** and **166** from among a plurality of different impedances in response to select signals **34** provided by CPU **30**.

Optional propagation delay elements **164** and **168** can be employed to test the timing sensitivity of DUT **14** to various propagation delays that result, for example, from different installation locations of RAC **112** on the Rambus™ channel. As illustrated, the operational effects of introducing various different propagation delays into the signal path between connector **154** and variable V_{TERM} supply **74** or the signal path between connector **154** and RAC **112** can be tested through selection of trace run lengths by selectors **160** of propagation delay elements **164** and **168**. As with impedances **162** and **166**, the select signals **34** that control selectors **160** of propagation delay elements **164** and **168** are supplied by CPU **30**. In an alternative embodiment of the present invention, the installation of DUT **14** at various locations on the Rambus™ channel can be simulated by including within connector **24** a series of dummy packaged devices that can be connected to the Rambus™ channel in a selectable order relative to DUT **14**. In this manner, testing can simulate the installation of RAC **112** as the device closest to DUT **14**, second closest to DUT **14**, etc.

With reference now to Figure 4, there is illustrated a high-level logical flowchart of an exemplary test process for testing logic with memory controller circuits, either on wafer

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or in packaged devices, utilizing tester 10 from **Figure 1**. As illustrated, the process begins at block **180** and then proceeds to block **182**, which depicts CPU **30** setting parameters for a DC test of DUT **14**. Power is then supplied to DUT **14**, as shown at block **184**. At block **186**, tester **12** performs a DC parametric test upon a DUT **14** while the DUT **14** is idle. To perform the DC parametric tests for an exemplary logic device having a Rambus™ memory controller, CPU **30** sets relays **92** to connect the output pins of DUT **14** to PMUs **80** rather than RAC **112**. PMUs **80** may then be utilized to measure the power dissipation of DUT **14** for one or more sets of V_{REF} , V_{DD} and V_{DDA} voltages, as well as the leakage current of the pins of DUT **14**. These power and current measurements are then transferred to sequencer **100** via unillustrated connections for storage in RAM **104** and comparison with acceptable values to obtain a pass/fail determination.

The process proceeds from block **186** to block **188**, which depicts powering down DUT **14**. If at block **190**, a determination is made that the DC test results indicate DUT **14** failed, the process branches to block **222** to process DUT **14** as a failure. If, however, DUT **14** passed the DC test and additional DC tests are to be performed, the process returns from decision block **192** to continue the loop comprising blocks **180** through **190** until all DC parametric testing is complete.

Following DC parametric testing, AC parametric testing may be performed, as depicted at blocks **194-206**. At block **194**, DUT **14** is powered on in order to perform a vector-based self-test. Block **196** illustrates CPU **30** setting the AC parameters to be utilized during the vector-based self-test. The vector-based self-test is then performed as illustrated at block **198** (which is described below), and the results are collected at block **200**. As represented by decision block **202**, logic testing using vectors (and each of the other AC tests) is preferably performed with multiple different sets of AC parameters in order to assess the proper operation of DUT **14** over a wide range of AC parameters. For DUTs **14** comprising logic devices with Rambus™ memory controllers, the AC parameters that can be varied during AC testing include those summarized below in Table I. Of course, for different DUTs, other or additional AC parameters can be tested.

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TABLE I

AC parameter	Description
T_{CYCLE}	transfer clock frequency
T_{SH}	combined setup and hold times for DUT (i.e., period defining valid WRITE data)
T_{Q}	time to valid data output (i.e., period defining valid READ data)
T_{TR}	time from transmit to receive (i.e., interval between consecutive READ and WRITE operations)
V_{REF}	reference voltage that defines midpoint between the logic low input voltage (V_{IL}) and logic high input voltage (V_{IH})
V_{TERM}	termination voltage for Rambus™ channel

CPU 30 sets the T_{CYCLE} parameter by generating appropriate clock selects 38 to select clock sources 122 of desired frequencies to supply clocks 120. In a typical testing scenario, it is desirable to select transfer clock frequencies below, at, and above the rated clock frequency of DUT 14. For example, for a DUT 14 using Rambus™ memory modules having a rated clock frequency of up to 533 MHz, it is desirable to perform testing at a number of transfer clock frequencies ranging from approximately 300 MHz to approximately 584 MHz.

In order to test the sensitivity of DUT 14 to the timing of WRITE operations, CPU 30 stresses the T_{SH} parameter by generating a TL delay signal 40 that selects a delay applied to the clock-from-master (CFM) and complementary clock-from-master negative (CFMN) signals 130 by delay 134. As shown in Figure 5A, which illustrates signal timing without any delay, the high-to-low crossing of CFM with CFMN defines a timing of a valid period during which data (e.g., ROW, COL, DQA and DQB) and commands are generated by DUT 14. The extent of the valid period is equal to the sum of a setup time (t_{s}) prior to the crossing of CFM and CFMN during which the data and commands must be valid and a hold time (t_{h}) following the crossing of CFM and CFMN during which the commands must be stable. As shown in Figure 5B, the sensitivity of DUT 14 to variations in WRITE timing can be tested by applying a delay to CFM and CFMN equal to a full cycle minus Δt_1 . By doing so, the setup time (t_{s}) is effectively decreased by Δt_1 , and the timing sensitivity of

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DUT 14 can be evaluated.

CPU 30 similarly tests the timing sensitivity of DUT 14 during READ operations by stressing the T_Q parameter through generation of DUT delay signal 42 to select the delay applied by delay 136 to the clock-from-master (CTM) and the complementary clock-from-master negative (CTMN) signals 132 output to DUT 14 by RAC 112. As illustrated in **Figure 6A**, which depicts signal timing without any applied delay, the high-to-low crossing of CTM with CTMN defines a timing of a period (t_Q) during which data (i.e., DQA and DQB) output by RAC 112 are valid for sampling by DUT 14. The extent of the valid period t_Q is equal to the period of CTM minus the two intervals $t_{Q, MIN}$ and $t_{Q, MAX}$. As shown in **Figure 6B**, the sensitivity of DUT 14 to variations in READ timing can be tested by applying a delay to CTM and CTMN equal to a full cycle minus Δt_2 . By doing so, the valid period (t_Q) is effectively decreased by Δt_2 , and the timing sensitivity of DUT 14 can be evaluated.

CPU 30 tests the T_{TR} parameter by shifting the phase of CTM/CTMN relative to CFM/CFMN utilizing appropriate delay signals 40 and 42. By varying the relative timing of these clock signal pairs by small increments, CPU 30 can test DUT 14 for worst-case failures for consecutive READ and WRITE operations.

V_{REF} and V_{TERM} are set by CPU 30 utilizing voltage select signals 44 in order to test DUT 14 for supply voltage margin and launch voltage sensitivity, respectively. As discussed further below with reference to **Figures 25** and **26**, because DUT 14 calibrates V_{IL} and V_{IH} to V_{REF} , varying V_{REF} also tests the sensitivity of DUT 14 to various input voltage levels without the need to actually vary the voltage levels of the data inputs provided to DUT 14.

Referring again to **Figure 4**, after the AC parameters are set at block 196, CPU 30 downloads vector data and correct test results to sequencer 100, which stores them in memory 110. To exercise the self-test circuitry of DUT 14, sequencer 100 causes RSL bus master 114 to stimulate appropriate input pins of DUT 14 with the vector data at block 198.

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In addition, sequencer **100** tests the sensitivity of DUT **14** to various timings, voltages, impedances, and propagation delays. For exemplary logic devices having Rambus™ memory controllers, the probability of failure during testing can be increased or decreased by:

- (1) varying termination impedance **162** and test impedance **166** while maintaining the characteristic impedance of an end-use environment or varying the impedance from the characteristic impedance of the end-use environment in order to affect the amplitude of the Rambus™ channel reflections; and/or
- (2) varying the delay applied by delay elements **164** and **168** to simulate different locations of DUT **14** on the Rambus™ channel, which affects the timing of reflections on the Rambus™ channel relative to the output of DUT **14**; and/or
- (3) varying V_{TERM} either above or below the standard value of $1.8 \pm 0.1V$.

Sequencer **100** causes RSL bus master **114** to log the results of the vector-stimulated self-test as shown in block **200**. As illustrated at block **202**, CPU **30** may then alter the AC parameters and repeat the vector-stimulated self-test utilizing the new AC parameters. When both the AC sets and vectors sets are complete, sequencer **100** powers down DUT **14** at block **204** and compares the test results with the correct results to produce a pass/fail determination at block **206**. The process then branches to block **222** if a failure is detected and continues on to block **208** otherwise.

Block **208** depicts CPU **30** storing a test program into a section of memory **110** that can be accessed by DUT **14**. Blocks **210-212** illustrate CPU **30** setting initial AC parameters for AC parametric testing and causing power to be supplied to DUT **14**. At block **214**, DUT **14** is directed to execute the test program stored in memory **110** and write output results into memory **110**. Following execution of the test program, CPU **30** powers down DUT **14** at block **216**. As represented by decision block **218**, the process returns to block **208** and executes the loop continuing through block **216** until all AC parametric sets are complete for all test program sequences. After all AC parametric tests and test program sequences are complete, sequencer **100** finally compares the test results with the correct

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results to produce a pass/fail determination at block 220. The process branches to block 222 if a failure is detected and continues to block 224 to process the DUT 14 as "passing" otherwise.

The test program sequences used in loop comprising blocks 208 through 218 can include functional tests, command sets, or pattern-based tests. For example, for a logic device having a Rambus™ memory controller, the pattern-based tests can include the individual tests summarized below in Table II. In a typical pattern-testing embodiment, CPU 30 downloads the test program sequences and data patterns to sequencer 100 for storage in memory 110 at block 208. CPU 30 then establishes initial AC parameters for Rambus™ core accesses at block 210. DUT 14 is powered up at block 212, and as depicted at block 214, DUT 14 begins to read from memory 110 and execute the test sequence to issue WRITE and READ operations to verify correct operation of DUT 14. Results of the pattern testing are written into memory 110.

TABLE II

Rambus™ core test suite tests	Description
Address	ensures that all memory array locations can be accessed
Data	verifies that each memory bit operates as both a 1 and a 0
Refresh	memory array properly retains data
March algorithms	data patterns written into memory arrays match those read out of memory arrays
Disturb Neighborhood Sensitivity Test (DNST)	modifying contents of a memory cell in the memory array does not modify data stored in neighboring memory cells

Similarly for a logic device with Rambus™ memory controller, the test program sequences, which typically include channel command sets and correct results, are transferred by CPU 30 to sequencer 100 for storage in memory 110, as shown at block 208 of Figure 4. As represented at block 214, DUT 14 executes the Rambus™ channel

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commands from memory 110 and writes the results to memory 110.

Lastly for a logic device with Rambus™ memory controller, the test sequence used in block 214 by DUT 14 may also perform additional Rambus™ functional tests that verify DUT 14 works properly with the special functionality of Rambus™ memory. A number of these Rambus™ functional tests are summarized below in Table III.

TABLE III

Rambus™ functional tests	Description
Bank interleave	verify bank addressing of all memory banks
Write/Retire	checks operation of write retire buffer
Byte Operation Mask	verifies operation of mask programmed via the Rambus™ COLM bus
NAP and Power Down	assures operation in low-power modes

After the loop of blocks 208 through 218 has been completed all functional tests, command sets, or pattern-based test sequences for all desired sets of AC parameters, the test process shown in Figure 4 ends at block 220, which depicts sequencer 100 relaying the pass/fail determinations from blocks 224 and 222, respectively, to CPU 30, which reports the pass/fail determinations for this DUT 14 to host 16.

Referring now to Figure 7, there is depicted a high-level block diagram of a host-based memory tester 250 in accordance with a first alternative embodiment of the present invention. Like reference numerals are utilized in Figure 7 to identify elements that are the same as or similar to those of the memory tester embodiment illustrated in Figures 1-3.

As shown, memory tester 250 comprises a host 16' and a tester logic board 254. Host 16', which may comprise, for example, a conventional personal computer system or other data processing system, includes a system board 252 having an interconnect 258 to which a CPU 30, memory 110, and peripheral adapter 260 are coupled for communication. Peripheral adapter 260 is further coupled to a storage device 262, which provides non-

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volatile storage for test procedures, test parameters, and test data. Memory 110 is coupled to RAC 112, which is in turn connected to a standard Rambus™ channel 257 communicating with a connector 256 mounted on system board 252. Bus master 114 is also connected to Rambus™ channel 257.

Memory tester 250 employs a host-based tester architecture that permits CPU 30 of host 16' to test a logic DUT having an Rambus™ memory controller DUT 14 as if DUT 14 were mounted on a standard board with Rambus™ channel through the installation, in connector 256, of a tester logic board 254 having an impedance-controlled connector 24 for DUT 14. Like tester logic board 12 of Figure 2, tester logic board 254 includes a cooling subsystem 48 and a power subsystem 52, as well as tester logic 50'. In the first alternative embodiment shown in Figure 7, tester logic 50' is greatly simplified as compared to tester logic 50 of Figure 2 in that no sequencer 100 is required and the memory 110 and RAC 112 utilized for testing are mounted on system board 252. The one major addition to tester logic 50' is a serial presence detect (SPD) emulation circuit 255 which may be needed to identify memory 110 and RAC 112 to DUT 14 as a Rambus™ memory module upon system reset. Information regarding the operation of SPD emulation circuit 255 may be found, for example, in *Direct Rambus™ SPD Specification*, rev. 1.1, Rambus, Inc., June 2000, which is incorporated herein by reference.

In operation, memory tester 250 utilizes the test information stored by storage device 262 (or remotely stored test information communicated via a network connection) to test DUT 14 according to the test process depicted in Figure 4 and described above. The major difference in the manner in which testing is performed by the embodiment of Figure 7 is that CPU 30 directly accesses memory 110 by issuing an appropriate request on interconnect 258. In response to the request by DUT 14 over Rambus™ channel 257, RAC 112 accesses memory 110 for read and write operations. CPU 30 can then compare the responses written into memory 110 by DUT 14 with expected results to make pass/fail determinations for the various tests. The first alternative embodiment shown in Figure 7 offers the use of specific system board, which may be a production environment for DUT 14.

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Referring now to **Figure 8**, there is depicted a high-level block diagram of a host-based memory tester **250** in accordance with a second alternative embodiment of the present invention. In **Figure 8**, like reference numerals are utilized to identify elements that are the same as or similar to those of the memory tester embodiment illustrated in **Figures 1-3** and **Figure 7**. **Figure 8** differs from **Figure 7** in the use of Rambus RDRAM memory devices **266**, rather than a discrete RAC **112** and memory **110**. Access by CPU **30** to Rambus RDRAMs **266** is now through Rambus controller **231** and RAC **112**. The second alternative embodiment shown in **Figure 8** offers the use of specific system board, which may be a production environment for DUT **14**.

Referring now to **Figure 9**, there is depicted a high-level block diagram of a host-based memory tester **250** in accordance with a third alternative embodiment of the present invention. In **Figure 9**, like reference numerals are utilized to identify elements that are the same as or similar to those of the memory tester embodiment illustrated in **Figures 1-3** and **Figures 7-8**. As shown in **Figure 9**, CPU **30** is located on system board **252**, while memory **110** is located on peripheral board **264**, which connects to DUT **14** by means of tester logic board **254**. CPU **30** accesses memory **110** through peripheral interconnect **265**. CPU **30** accesses peripheral interconnect **265** through local interconnect **258** and peripheral controller **259**. Peripheral interconnect **265** accesses memory **110** through peripheral controller **263** and local interconnect **261**. The third alternative embodiment shown in **Figure 9** offers the use of specific combinations of system and peripheral boards, which may be a production environment for DUT **14**.

Referring now to **Figure 10**, there is depicted a high-level block diagram of a host-based memory tester **250** in accordance with a fourth alternative embodiment of the present invention. In **Figure 10**, like reference numerals are utilized to identify elements that are the same as or similar to those of the memory tester embodiment illustrated in **Figures 1-3** and **Figure 9**. **Figure 10** differs from **Figure 9** through the use of Rambus RDRAM memory devices **266**, rather than discrete RAC **112** and memory **110**. Access by CPU **30** to the Rambus RDRAMs **266** is now through Rambus controller **231** and RAC **112**.

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Referring now to **Figure 11A**, there is depicted a high-level block diagram of a first embodiment of test fixture embodiment capable of testing a DUT **14** already manufactured onto a circuit board. DUT **14** is able to communicate with a logic tester **250** through connection to an unpopulated device site on the Rambus channel **270**. **Figure 11B** is a more detailed depiction of an unpopulated device site **270** on the Rambus channel having a plurality of pads, including pad **272**. **Figure 11C** shows a single finger of a controlled impedance probe **274**, which interfaces with connector **24** of logic tester **250** by contacting pad **272**. The controlled impedance probe **274** allows DUT **14** to communicate with logic tester **250** via unpopulated device site on the Rambus channel **270** as if DUT **14** was directly connected to the connector **24** of logic tester **250**. The test fixture embodiment shown in **Figures 11A-11C** offers the ability to test many functions of system board **252** or peripheral board **264** after DUT **14** is manufactured onto the circuit board.

Referring now to **Figure 12A**, there is depicted a high-level block diagram of a second embodiment of a test fixture capable of testing a DUT **14** already manufactured onto a circuit board. DUT **14** is able to communicate with logic tester **250** through connection to an unpopulated Rambus connector **276**, such as a socket for a Rambus memory module. **Figure 12B** shows a more detailed depiction of an unpopulated Rambus connector **276** for a Rambus memory module. Controlled impedance fixture **276** interfaces with connector **24** of logic tester **250** by contacting unpopulated Rambus connector **276**, thereby allowing DUT **14** to communicate with logic tester **250**. This second embodiment allows DUT **14** to communicate with logic tester **250** via unpopulated Rambus connector **276** as if DUT **14** were directly connected to the connector **24** of logic tester **250**. The second alternative embodiment fixture for testing DUT **14** shown in **Figures 12A-12B** offers the ability to test many functions of system board **252** or peripheral board **264** after DUT **14** is manufactured onto the circuit board.

Referring now to **Figure 13**, there is illustrated a more detailed block diagram of a tester logic board **12** from **Figure 1** in accordance with a second preferred embodiment of the present invention. In **Figure 13**, like reference numerals are utilized to identify elements that are the same as or similar to those of the memory tester embodiment

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illustrated in **Figures 1-2**. The depicted embodiment includes circuitry specifically designed for testing logic DUTs having integrated Double Data Rate (DDR) synchronous DRAM memory control circuitry; however, those skilled in the art will appreciate that the present invention is not limited to testing logic DUTs having DDR memory controllers, but is instead applicable to testing other types of integrated circuitry. References useful for an understanding of the depicted embodiment of the present invention include the following DDR documentation (which is incorporated herein by reference):

- a) *JEDEC standard JESD79: Double Data Rate (DDR) SDRAM Specification*, release 1, JEDEC Solid State Technology Association, June 2000;
- b) *JEDEC standard No. 21-C: 4.5.10 – 184 Pin Unbuffered DDR SDRAM DIMM FAMILY*, release 9, JEDEC Solid State Technology Association, pages 4.5.10–1 to 4.5.10–17;
- c) *Application Note XAPP200: Virtex Series and Spartan-II Family: Synthesizable 1.6 GBytes/s DDR SDRAM Controller*, ver. 2.3, Xilinx Inc., Jennifer Tran, March 21, 2000;

As shown in **Figure 13**, tester logic board **12** differs from that illustrated in **Figure 2** in that elements specific to logic devices using RSL transfers, including memory **110**, RAC **112**, RSL bus master **114**, control signals for the RSL bus master **116**, clocks **120**, CFM signal **130**, CTM signal **132**, CFM delay **134**, and CTM delay **136**, are eliminated. New elements illustrated in **Figure 13** for logic devices using communication over a DDR memory bus include DDR memory controller **230**, DDR memory devices **232**, DDR bus master **234**, control signals **236** for DDR bus master **234**, data and strobe signals (DQ_IN and DQS_IN) **242**, DQ_IN and DQS_IN delay circuits **238**, delayed data and strobe signals (DQ_IN and DQS_IN) **246** into the tester logic, data and strobe signals (DQ_OUT and DQS_OUT) **244**, DQ_OUT and DQS_OUT delay circuits **240**, delayed data and strobe signals (DQ_OUT and DQS_OUT) **248** into DUT **14**, and clocks **268**. In addition, the voltages output by the variable power supplies (elements **72-78**) and the characteristic impedance of the apparatus are changed from those appropriate for logic devices using RSL transfers to those for logic devices using communication over a DDR memory bus.

Accesses by DUT **14** for WRITE operations to and READ operations from DDR memory devices **232** permit testing of logic DUTs having integrated DDR memory control

circuits utilizing the methodology illustrated in **Figure 4**. In order to test the sensitivity of DUT **14** to the timing of WRITE operations, CPU **30** stresses the T_{DS} and T_{DH} parameters by generating a TL delay signal **40** that selects delays separately applied to DQ_IN and DQS_IN **242** by delay devices **238**. As illustrated in **Figure 14A**, which depicts signal timing without any delay, the high-to-low crossing of CK with /CK defines a timing of a valid period during which data (DQ) and strobe (DQS) are generated by DUT **14**. The extent of the valid period is equal to the sum of a setup time (t_{DS}) prior to the crossing of CK and /CK during which the data must be valid and a hold time (t_{DH}) following the crossing of CK and /CK during which the data must be stable. As shown in **Figure 14B**, the sensitivity of DUT **14** to variations in WRITE timing can be tested by applying delays separately to data DQ_IN (Δt_1) and strobe DQS_IN (Δt_2) in such a manner that Δt_1 is greater than Δt_2 . By doing so, the setup time (t_{DS}) is effectively decreased by the difference Δt_1 minus Δt_2 , and the timing sensitivity of DUT **14** for the setup time (t_{DS}) can be evaluated. Similarly, the required hold time (t_{DS}) for successful WRITE operations may be effectively forced longer by delaying strobe DQS_IN longer than data (DQ_IN).

CPU **30** similarly tests the timing sensitivity of DUT **14** during READ operations by stressing the T_{DQSQ} and T_{QH} parameters through generation of DUT delay signal **42** to select the delay applied by delay devices **240** separately to the DQ_OUT and DQS_OUT signals **244** output to DUT **14** by DDR memory devices **232**. As illustrated in **Figure 15A**, which depicts signal timing without any applied delay, the high-to-low crossing of CK and /CK defines the timing of a period during which data (DQ) and strobe (DQS) output by DDR memory devices **232** are valid for sampling by DUT **14**. As shown in **Figure 15B**, the sensitivity of DUT **14** to variations in READ timing can be tested by applying delays separately to data DQ_IN (Δt_1) and strobe DQS_IN (Δt_2) in such a manner that Δt_1 is greater than Δt_2 . By doing so, the start of the valid data output (T_{QH} minus T_{DQSQ}) is effectively delayed by Δt_1 minus Δt_2 . This delay narrows the window between the start of valid data output (T_{DQSQ}) and the time at which DUT **14** expects completion of the READ operation, thereby permitting evaluation of the timing sensitivity of DUT **14** for successful READ operations.

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With reference now to **Figure 16**, a detailed depiction of a preferred embodiment of a connector **24** from **Figures 1 and 13** is given. The illustrated embodiment includes some major differences from the connector illustrated in **Figure 3**, corresponding to differences between communication over a DDR memory bus versus an interconnect conveying RSL transfers, as illustrated in **Figure 3**. For example, instead of RAC **112** being the termination point of transfers with DUT **14** as illustrated in **Figure 3**, DDR memory devices **232** are the termination point for data transfers in the embodiment shown in **Figure 16**. In addition, the voltage parameter determined by variable voltage supply **74** to test the sensitivity of DUT **14** is V_{REF} , which is selected by variable voltage supply **74** in response to voltage select signals **44** provided by CPU **30**. Since V_{REF} is applied to only one pin of exemplary logic device using communication over a DDR memory bus DUT **14**, elements **164** and **162** from **Figure 3** do not exist in **Figure 16**.

In accordance with an important aspect of the present invention and as illustrated in **Figure 16**, the input impedance presented by each connection **154** of site **150** is equivalent to the characteristic impedance of an end-use environment of DUT **14**. For example, if the end-use environment is a socket connection for JEDEC standard DDR modules, such as an 184-pin unbuffered DDR SDRAM DIMM, the characteristic impedance is selected to be approximately $60\ \Omega$, and more particularly, $60\ \Omega \pm 10\%$.

Optional propagation delay element **168** and optional impedance element **166** can be employed to test the sensitivity of DUT **14** to various propagation delays and impedances that result, for example, from different installation locations of DDR memory devices **232** on the DDR memory bus. In an alternative embodiment of the present invention, the installation of DUT **14** at various locations on the DDR memory bus can be simulated by including within connector **24** a series of dummy packaged devices that can be connected to the DDR memory bus in a selectable order relative to DUT **14**. In this manner, testing can simulate the installation of DDR memory devices **232** as the memory device or module closest to DUT **14**, second closest to DUT **14**, etc.

Referring now to **Figure 17**, there is depicted a high-level block diagram of a host-

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based memory tester 250 employing DDR memory in accordance with a first alternative embodiment of the present invention. In **Figure 17**, like reference numerals are utilized to identify elements that are the same as or similar to those of the host-based memory tester embodiment illustrated in **Figure 7**. Changes made to the embodiment shown in **Figure 7** to support a DUT 14 that employs DDR communication instead RSL transfers include replacement of connector 256 with connector 292, standard Rambus™ channel 257 with DDR memory bus 290, RSL bus master 114 with DDR bus master 234, and the combination of memory 110 and RAC 112 with DDR memory controller 230 and DDR memory devices 232, respectively. In addition, fundamental changes to system board 294 that are not important to the present invention make it distinctly different from system board 252 illustrated in **Figure 7**.

Referring now to **Figure 18**, there is depicted a high-level block diagram of a host-based memory tester 250 employing DDR memory in accordance with a second alternative embodiment of the present invention. In **Figure 18**, like reference numerals are utilized to identify elements that are the same as or similar to those of the host-based memory tester embodiment illustrated in **Figure 9**. However, there are a number of differences between the embodiments shown in **Figures 9** and **18** that reflect the use of DDR communication in the embodiment of **Figure 18** instead of the RSL transfers employed in the embodiment illustrated in **Figure 9**. These differences include replacement of connector 256 with connector 292, standard Rambus™ channel 257 with DDR memory bus 290, RSL bus master 114 with DDR bus master 234, and the combination of memory 110 and RAC 112 with DDR memory controller 230 and DDR memory devices 232, respectively. In addition, fundamental changes to system board 294 and peripheral board 296 that are not important to the present invention make them distinctly different from system board 252 and peripheral board 264 illustrated in **Figure 9**.

Referring now to **Figure 19A-19C**, there is depicted a first embodiment of a test fixture for testing DUTs 14 that employ communication over a DDR memory bus, where the DUTs are manufactured onto circuit boards. As can be seen by comparison of **Figure 19A** with **Figure 11A**, the two test fixture embodiments are somewhat similar. However, in

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order to support use of DDR communication in the embodiment of **Figure 19A**, there are a number of differences from the embodiment illustrated in **Figure 11A**. These differences include replacement of unpopulated device site **270** on the Rambus channel with unpopulated device site **298** on the DDR memory bus. Fundamental changes to system board **294** and peripheral board **296** not important to the present invention make them distinctly different from system board **252** and peripheral board **264** illustrated in **Figure 11A**.

Figure 19B depicts a more detailed view of unpopulated site **298** on the DDR memory bus. As shown, the plurality of connections at unpopulated site **298** include pad **300**. As shown in **Figure 19C**, a single finger **302** of a controlled impedance probe contacts pad **300**, while other unillustrated fingers contact others of the plurality of pads in unpopulated site **298**. This arrangement allows DUT **14** to communicate with logic tester **250** via unpopulated device site **298** on the DDR memory bus as if DUT **14** were directly connected to a connector **24** of logic tester **250**.

Referring now to **Figure 20A**, there is depicted a second embodiment of a test fixture for testing DUTs **14** using communication over a DDR memory bus, where the DUTs are manufactured onto circuit boards. As can be seen by comparison of **Figure 20A** with **Figure 12A**, the two test fixture embodiments are somewhat similar. However, in order to support use of DDR communication in the embodiment of **Figure 19A**, there are a number of differences from the RSL embodiment illustrated in **Figure 12A**. These differences include replacement of unpopulated Rambus connector **276** with unpopulated DDR connector **298**, which may be a socket for a DDR memory module. Fundamental changes to system board **294** and peripheral board **296** that are not essential for an understanding of the present invention make them distinctly different from system board **252** and peripheral board **264** of **Figure 12A**. **Figure 20B** depicts a more detailed view of the connection of a controlled impedance test fixture **304** within DDR connector **298** of **Figure 20A**.

The present invention is also applicable to testing logic devices using an alternative timing as shown in **Figure 21A**. The illustrated signal timing differs from the Rambus

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Signaling Levels (RSL) transfers illustrated in **Figure 5A** in that more than 2 data transfers are permitted per clock cycle, as with Quad RSL (QRSL) signaling. The present invention permits tester logic 50 or 50' to perform WRITE and READ transfers with DUT 14, for the purpose of testing the operation of DUT 14 with great emulation of the end use environment. **Figure 21A** shows timing for a WRITE operation without any delay relative to the phase of the clock signal from DUT 14. **Figure 21B**, by contrast, depicts testing the sensitivity of DUT 14 to variations in WRITE timing by applying a delay to CFM and CFMN equal to a full cycle minus Δt_1 . By doing so, the setup time (t_s) is effectively decreased by Δt_1 , and the timing sensitivity of DUT 14 can be evaluated.

Referring now to **Figures 22A-22B**, timing diagrams showing DUT 14 using memory transfers more frequent than 2 per clock cycle are illustrated. With this signal timing, the timing sensitivity during READ operations is tested by stressing the T_Q parameter through delays to the clock-from-master (CTM) and the complementary clock-from-master negative (CTMN) signals 132 output to DUT 14. **Figure 22A** depicts signal timing without any applied delay. As shown in **Figure 22B**, the sensitivity of DUT 14 to variations in READ timing can be tested by applying a delay to CTM and CTMN equal to a full cycle minus Δt_2 so that t_Q is effectively decreased and the timing sensitivity of DUT 14 can be evaluated.

The present invention is also applicable to testing logic devices using an alternative memory technology timing as shown in **Figure 23A**. The illustrated signal timing differs from the double data rate (DDR) synchronous signaling illustrated in **Figure 14A** in that more than 2 data transfers per clock cycle are allowed, as in Quad Data Rate (QDR) memory technology. The present invention permits the tester logic 50 to perform WRITE and READ transfers with DUT 14, for the purpose of testing the operation of DUT 14 with great emulation of the end use environment. **Figure 23A** shows timing for a WRITE operation without any delay to strobe (DQS). **Figure 23B**, by contrast, depicts testing the sensitivity of DUT 14 to variations in WRITE timing by applying delays separately to data DQ_IN (Δt_1) and strobe DQS_IN (Δt_2) in such a manner that Δt_1 is greater than Δt_2 . By doing so, the setup time (t_{DS}) is effectively decreased and the timing sensitivity of DUT 14 for the setup

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time (t_{DS}) can be evaluated. Similarly the required hold time (t_{DS}) for successful WRITE operations may be effectively forced longer by delaying strobe DQS_IN longer than data (DQ_IN).

Referring now to **Figures 24A-24B**, timing diagrams showing DUT 14 using more than 2 memory transfers per clock cycle are depicted. The embodiment of the present invention shown in **Figure 13** can be employed to test the timing sensitivity of DUT 14 during READ operations by stressing the TDQSQ and TQH parameters through generation of delays separately to the DQ_OUT and DQS_OUT signals 244 output to DUT 14 by memory devices 232. **Figure 24A** depicts signal timing without any applied delay. As shown in **Figure 24B**, the sensitivity of DUT 14 to variations in READ timing can be tested by applying delays separately to data DQ_IN (Δt_1) and strobe DQS_IN (Δt_2) to narrow the window between the start of valid data output (TDQSQ) and the time at which DUT 14 expects completion of the READ operation. By narrowing the window in this manner, the timing sensitivity of DUT 14 for successful READ operations can be evaluated.

With reference now to **Figure 25**, a voltage chart is given that illustrates the effect varying V_{REF} has on the apparent voltage levels of inputs of a DUT 14 that uses Rambus Signaling Levels (RSL) transfers. The apparent input voltage for the high logic state (V_{DIH}) to DUT 14 for an actual voltage of 1.8 V varies linearly with a slope of 1.0 as V_{REF} varies around 1.40 V. The apparent input voltage for the low logic state (V_{DIL}) to DUT 14 for actual voltage of 1.0 V varies linearly with a slope of 1.0 as V_{REF} varies around 1.40 V. In this manner, the sensitivity of DUT 14 to a variation in input voltage from external devices employing RSL signaling can be tested.

Figure 26 illustrates a voltage chart showing the effect varying V_{REF} has on the apparent voltage levels of inputs of a DUT 14 that employs double data rate (DDR) synchronous dynamic memory bus transfers. The apparent input voltage for the high logic state (V_{IH}) to DUT 14 for actual voltage of 1.8 V varies linearly with a slope of 1.0 as V_{REF} varies around 1.25 V. The apparent input voltage for the low logic state (V_{IL}) to DUT 14 for actual voltage of 0.7 V varies linearly with a slope of 1.0 as V_{REF} varies around 1.25 V.

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Thus, by varying V_{REF} in accordance with the present invention, the sensitivity of DUT 14 to a variation in input voltage from external devices using DDR or a derivative can be efficiently tested.

5 While the invention has been particularly shown and described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention. For example, although aspects of the present invention have been described with respect to a tester system executing software that directs the functions of the present invention,
10 it should be understood that the present invention may alternatively be implemented as a program product for use with a data processing system. Programs defining the functions of the present invention can be delivered to a data processing system via a variety of signal-bearing media, which include, without limitation, non-rewritable storage media (e.g., CD-ROM),
rewritable storage media (e.g., a floppy diskette or hard disk drive), and communication media,
15 such as digital and analog networks. It should be understood, therefore, that such signal-bearing media, when carrying or encoding computer readable instructions that direct the functions of the present invention, represent alternative embodiments of the present invention.